OBSERVATIONS IN IMPROVED GEOLOCATION ACCURACY BASED ON SIGNAL-DEPENDENT AND NON-SIGNAL DEPENDENT ERRORS

Lauren E. Porr*, Gregory P. Faragher, John A. Kosinski
RDECOM CERDEC I2WD
Ft. Monmouth, NJ 07703

John J. Borowick
CACI Technologies, Inc.
Eatontown, NJ 07724

ABSTRACT

The effects of signal-dependent and non-signal dependent errors on geolocation are examined. The results provide a focus for research in improvements of geolocation accuracy.

1. INTRODUCTION

Geolocation of RF emitters is a well-known discipline with significant humanitarian interest in, for example, the location of 911 calls on land and SOS signals at sea. In most cases, the accuracy of the geolocation as measured in terms of the miss distance between the reported geolocation and the true location of the emitter is the primary system performance specification. Other significant factors include the amount of signal required for successful geolocation (both in terms of signal-to-noise ratio (SNR) and signal duration), the time required to process the data to determine a geolocation, and the number of separate receiver platforms that must collect the signal. In the case of at sea search and rescue operations, the geolocation accuracy directly determines the extent of the region that must be grid searched and directly affects the speed with which rescuers can be expected to arrive at the aid of those in distress. It is not surprising that this field demands ever improved geolocation accuracy.

This paper examines the effects of signal-dependent versus non-signal-dependent errors on the geolocation accuracy that a state-of-the-art system based on Commercial-Off-the-Shelf (COTS) equipment can potentially achieve. The results provide a focus for research in improvements of geolocation accuracy. The studies make use of a simulation tool developed by the Intelligence and Information Warfare Directorate (I2WD) at Ft. Monmouth, NJ; supported by CACI Technologies, Inc., Eatontown, NJ; and the Research Associates of Syracuse (RAS), Syracuse, NY. The Mathcad tool was developed for the purpose of examining the propagation of a signal between a transmitter and receiver given specific environmental characteristics.

2. GEOLOCATION

There are a number of well-known approaches for the geolocation of RF emitters. These include the simple and popular direction-finding and triangulation techniques used by radio amateurs and ranging via timing techniques being applied to modern E911 systems. The focus here is on Time Difference of Arrival (TDOA) and Frequency Difference of Arrival (FDOA) systems. Such systems provide rapid and accurate geolocation, but at the cost of requiring simultaneous signal collection by multiple receiver platforms.

TDOA geolocation is based upon the use of two receivers with strict synchronization. The difference in time between when a signal is detected by one receiver as compared to another defines a *hyperbolic* TDOA line of position (LOP) along which the emitter must lie. FDOA works similarly in examining the signal copies as received at two receivers with precision frequency control. The different Doppler shifts arising from the varying relative motions between the emitter and all of the receivers are determined. In contrast to the TDOA solutions, the Doppler shifts are used to create *parabolic* FDOA LOPs along the ground. The intersections of sets of TDOA and FDOA LOPs determine candidate geolocations for an RF transmitter, with ambiguities among multiple intersections resolved through the use of multiple receiver pairs. The basic concept is illustrated in Figure 1.

Report Documentation Page

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
00 DEC 2004	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Observations in Improved Geolocation Accuracy Based on Signal-Dependent and Non-Signal Dependent Errors	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
RDECOM CERDEC 12WD Ft. Monmouth, NJ 07703; CACI Technologies, Inc. Eatontown, NJ 07724	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001736, Proceedings for the Army Science Conference (24th) Held on 29 November - 2 December 2005 in Orlando, Florida. , The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

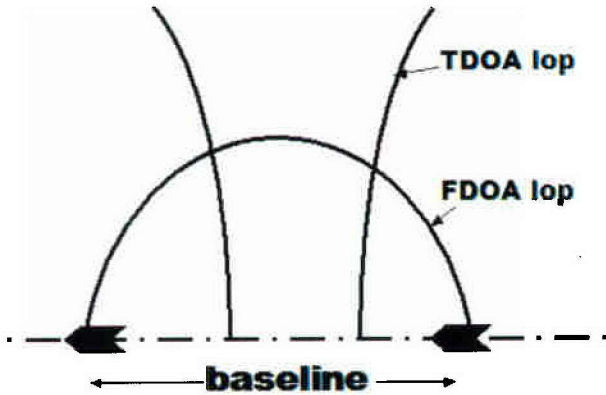| 16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	**UU**	**4**	
unclassified	**unclassified**	**unclassified**			

Figure 1. TDOA and FDOA LOPs.

Errors in geolocation are introduced by the presence of other interfering RF signals and factors such as weather. As a result, geolocation is undertaken as a statistical process based upon the analysis of many sets of LOPs or reported emitter locations. Over time, the reported locations will (hopefully) concentrate around the true position of the target. The distribution of the reported locations as compared to the true location determines the geolocation accuracy, which is stated in terms of either a circle or an ellipse centered at the true emitter location, and containing a specified fraction of reported locations. The size of the circle or ellipse is the standard by which geolocation accuracy is judged, and is called the Circular Error Probable (CEP) or Elliptical Error Probable (EEP) for a stated fraction of enclosed locations, i.e. 50% CEP, 95% EEP, etc. The CEP and EEP actually characterize two significant quantities: 1) for a given true emitter location, where will the system report the emitter as being? and 2) for a given reported emitter location, how close is the true emitter location likely to be?

Errors in geolocation can be grouped into two categories: signal-dependent and non-signal-dependent errors. Signal-dependent errors are those errors that are related to the *as-received* RF waveform such as signal frequency, bandwidth and modulation, SNR, and the effects of the environment on the signal such attenuation due to rain or multi-path reflection due to terrain. Non-signal-dependent errors are those errors that are related to the mechanics of the geolocation system such as timing and synchronization, precision frequency control, position of the aircraft and geodesy.

3. ASSUMPTIONS

The analysis of geolocation errors as related to potential signal-dependent and non-signal dependent errors is a complicated process that requires the study of a large number of variables, not all of which are independent. For example, the noise figure of the receivers is independent of the navigational accuracy, but both system synchronization (timing accuracy) and

precision frequency referencing may derive from a single oscillator that is referenced to GPS. The role of each of these factors can be studied using the Mathcad-based simulation tool developed at I2WD. Here we present only one illustrative example that speaks to the relative impact of aggregated signal-dependent and non-signal-dependent errors. In order to show these effects, we consider a scenario using the following assumptions.

3.1. Aircraft Configuration and Area of Interest

Consider a scenario such as search and rescue where three aircraft are flying along a collinear baseline and listening at the same time for a distress signal. Consider two possible configurations for the aircraft: 1) a spacing of 75 km between adjacent aircraft, and 2) a spacing of 150 km between adjacent aircraft. These two configurations will help to demonstrate the trade-offs between the improved triangulation provided by an extended baseline (a non-signal-dependent factor) and the degradation in signal strength since some of the receivers are farther away using an extended baseline (a signal dependent factor). The Area of Interest (AOI) that is being searched extends from 50 km out to 500 km from the baseline, which for purposes of illustration is divided into a closer Zone 1 out to 250 km and farther Zone 2 beyond 250 km.. Figure 2 illustrates the baseline, the aircraft positions, the AOI, and Zones 1-2. The aircraft are assumed to be flying generally straight and level at an altitude of 10,000 m.
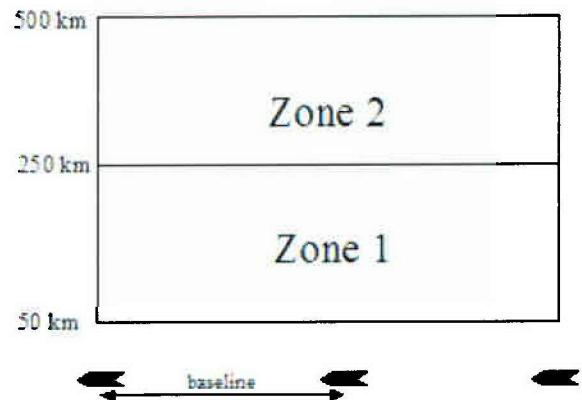

Figure 2. Aircraft Configuration and Area of Interest

Naturally, in addition to the position and altitude of the aircraft, the characteristics of the receivers are important factors affecting the accuracy of an LOP. Here we consider a generic COTS receiver whose characteristics are listed in Table 1. The aircraft employ GPS for position, navigation, and timing.

Table 1. Receiver Characteristics

Minimum Bandwidth (kHz)	10
Thermal Noise, kT (dBm/MHz)	-114
Number of Points over which CEP is calculated within the AOI	10,000

3.2 Transmitter Characteristics

In this illustration, the distress signal is transmitted by a commercial CB radio that has the following characteristics:

Table 2. Transmitter Characteristics

Moving?	No
Height (m)	2
Frequency (MHz)	27

The question of moving versus stationary impacts on both the Doppler measurements and the algorithm used to process the data, while the transmitter height and frequency impact on the received signal strength.

3.3 Environmental Characteristics

In many detection problems, the limiting process is random thermal noise. In the case illustrated here, there is a significant contribution from background galactic noise. The International Telecommunications Union (ITU) specifies the galactic noise as

$$N_G = 52 - 23 * \log (f_{MHz}) \text{ if } 5 \leq f_{MHz} \leq 130,$$
$$0 \text{ otherwise} \qquad (1)$$

For the 27 MHz signal, the excess galactic noise is 19 dB.

In addition, if the scenario is assumed to be a rural environment, there is excess man-made of noise in the area that can be estimated according to ITU-R PI.372-6 as

$$N_{rural} = 67.2 - 27.7 * \log (f_{MHz}) \text{ if } 0.3 \leq f_{MHz} \leq 250,$$
$$0 \text{ otherwise} \qquad (2)$$

At 27 MHz and in a rural setting, the excess man-made noise is 36 dB. At these frequencies, some particular systems engineering impacts occur. When this environmental noise factor is combined with a near isotropic gain antenna, the resultant receiver noise figure is severely degraded. On the other hand, with an inefficient receive antenna, the system noise figure is relatively that of the internal noise.

Signal propagation is dependent on the characteristics of the soil over which the wave propagates. For this illustration, consider average soil

with a permittivity and conductivity (Barton, Leonov, et al, 1997) of, respectively

$$\varepsilon_r = 15 \qquad (3)$$
$$\sigma = 0.005 \qquad (4)$$

3.4 Standard Error Contributors

Taking into account the specifications for a particular model COTS GPS receiver, the total reference errors for each category of error and for each type of LOP are as listed in Table 3.

Table 3. Total Reference Error Contributions

	TDOA	FDOA
Signal-Dependent	97.7 ns	0.6 mHz
Non-Signal-Dependent	14 ns	1.9 mHz

3.5 Geolocation Methodology

The analysis is based on the description of the scenario and certain other assumptions regarding the as-received SNR (which in turn depends upon assumptions regarding transmitted signal power, transmit and receive antenna types, receiver noise figure, etc.). The case where there are no signal-dependent errors is examined readily by selecting a very large SNR. The non-signal dependent errors are examined by comparing the results obtained assuming either reasonably available instrumentation errors (i.e., specifications of currently available COTS GPS) or a set of smaller instrumentation errors that are more technically challenging. The analysis considered spacing of 75 km or 150 km between adjacent aircraft. The results were examined in terms of CEPs.

4. PROCEDURES AND RESULTS

4.1 Procedures

The Mathcad-based simulation tool was used in the analysis presented here. For the first case considered, the parameters describing the scenario assuming 75 km aircraft spacing were entered into the simulation tool.

The worst-case scenario under these assumptions was established by applying all the reference errors as listed in Table 3 to the algorithms that generate the LOPs and obtaining the resulting CEPs. Figure 3 shows an example of the output from the Mathcad file. For the next case, the signal-dependent errors were removed and the averaged CEPs calculated as before. The third case examined the same scenario, with no signal-dependent errors, but with the aircraft spaced by 150-km. The fourth case examined the CEP results if, for the 150-km baseline, there are no signal-dependent errors and the non-signal dependent errors are halved. The results of the analyses are displayed in Table 4.
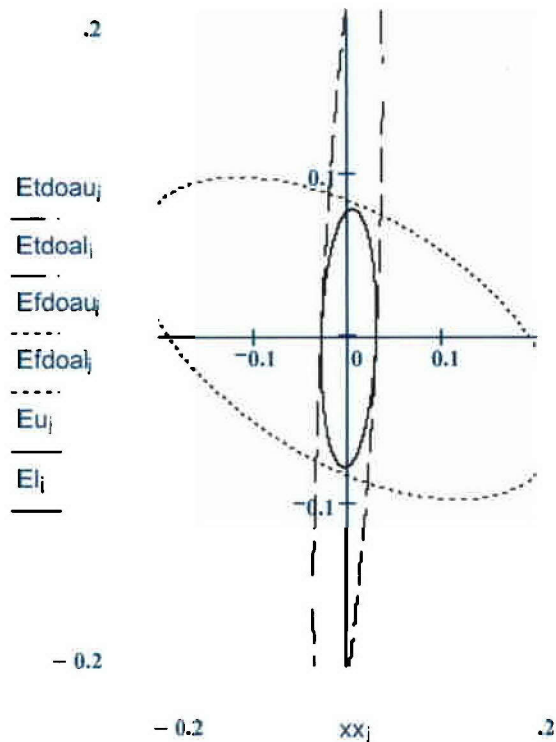
Figure 3. Example Output from Mathcad Tool

Table 4. CEP in Meters averaged for Each Zone

Error Type	Zone 1	Zone 2
Signal-dependent and current COTS non-signal-dependent errors, 75 km aircraft spacing	48	160
Current COTS non-signal-dependent error only, 75 km aircraft spacing	23	93
Current COTS non-signal dependent error only, 150 km spacing	14	43
"What if?" non-signal dependent error only assuming errors are reduced to ½ of current COTS, 150 km spacing	7	21

4.2 Results

The results as listed in Table 4 demonstrate a number of significant trends with regard to sources of geolocation errors. A note of caution is required with respect to the actual CEP values as listed: these are based upon a number of optimistic assumptions expected for a civilian search and rescue scenario (particularly with respect to as-received SNR) that will not be true for an actual military system, and thus the actual CEPs as listed

here are not representative of any current or planned military system as it would actually be employed in an operational scenario.

The results demonstrate the degree to which suppressing signal-dependent error improves the geolocation. This trend helps establish the relative return-on-investment (ROI) in improved antennas, lower noise figure receivers, etc. with application to emitter geolocation.

Similarly, substantial improvement comes from widening the baseline of aircraft spacing. This improvement is more significant for longer downrange distances. However, in order to use a longer baseline and not increase the signal-dependent errors also requires improved antennas, lower noise figure receivers, etc.

The most statistically significant improvement, however, is that once the remaining errors (that is, non-signal-dependent) are halved, the resultant CEP is halved. This trend indicates the relative ROI for continuing improvements in position, navigation, timing, geodesy, and precision frequency control as applied to emitter geolocation.

CONCLUSION

The contributions of signal-dependent and non-signal-dependent errors on geolocation accuracy have been examined. The significant trends relating the degree to which reduction in errors relate to improvements in accuracy have been identified. With additional detail, these studies enable the development of a technology base investment roadmap for the purposes of enhanced RF emitter geolocation.

5.   REFERENCES

Barton, David K., 1998, *Modern Radar System Analysis*, Artech House Publications.

Barton, David K., et al, 1 January 1997, *Radar Technology Encyclopedia,* Artech House Publications.

ITU Recommendation: Radio Noise, ITU-R PI 372-6.